

# Harvesting Technology and the Cost of Fuel Chips from Early Thinnings

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This study compared and analyzed the procurement cost of whole tree chips when using supply chains based on comminution at the roadside landing or at the terminal. It also identified the bottlenecks of the most common logging systems used in Finland. The study was done by using existing and published productivity parameters and models. The procurement cost calculations were made for a stand where the forwarding distance was 200 metres, removal of whole trees was 60 m<sup>3</sup> per hectare and the area of the stand was 2.0 hectares. The average size of the removed whole trees was 30 litres. The direct transport distance from the stand to the terminal or to the end use facility was 40 km while the secondary distance from the terminal to the end use facility was 10 km. A stumpage price for the harvested raw material was not included in this study. According to the study the cost of whole trees chips were 31.9–41.6 €/m<sup>3</sup> at the plant, or 14.9–19.4 €/MWh when the moisture content of chips was estimated to be 40%.

The two-machine system was found to be the most cost competitive logging system in pre-commercial thinnings thanks to both efficient cutting and, especially, forwarding work. In the manual worker based logging, the costs of felling bunching were the same as the mechanised system, whereas in forwarding the costs were almost double. Using the harwarder system the logging costs were found to be the highest, but in the larger tree volumes and removals the costs were almost equal to the manual worker based logging. The supply chain based on chipping at the roadside landing was more cost efficient compared to the chipping at the terminal system. The lower comminution cost at the terminal was not enough to cover the higher transportation cost of unprocessed material to the terminal, handling cost of chips at the terminal or the delivery cost to the end use facility.

**Keywords** costs, early thinnings, energy wood, harvesting, logging, productivity

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## 1 Introduction

Renewable energy sources clearly play an important role in the Finnish energy strategy as 20% of the primary energy consumed is derived from wood-based fuels (Finnish statistical yearbook of forestry 2006). Processing residues from the forest industry are the most important source of solid wood fuels (Ylitalo 2007) but these by-products can be considered as currently being fully utilised. Forest chips i.e.; logging residues, stumps from clear cuts and small-diameter trees from thinnings, are still a relatively modest source of fuel, but have considerable growth potential (Helynen et al. 2007). Thus, the most important means of increasing the consumption of wood for energy in the future is in the utilisation of forest chips resources. It has been estimated that the technical harvesting potential of forest chips is 16 million m<sup>3</sup> per year in Finland (Helynen et al. 2007).

The target of the Finnish energy and climate strategies is to increase the annual production of forest chips to 5 million m<sup>3</sup> by 2010 (Ministry of Trade and Industry 2000). It is estimated that if the production target is met, two thirds will be derived from above- and below-ground residues from the final harvest and one third from pre-commercial thinnings (Hakkila 2005). The Finnish Forest Council aims to further raise the production to 8 million m<sup>3</sup> by 2015 (Metsäsektorin tulevaisuuskuksaus 2006). The broad raw material base and the various sources of forest fuels guarantee the reliable delivery of forest chips as well as ensuring reasonable transport distances and costs. The current (2006) level of use of forest chips is 3.4 million m<sup>3</sup> per year with small-sized trees from thinnings constituting 23% of the forest chips raw material of heating and power plants (Ylitalo 2007).

A typical small-sized energy wood harvesting site in Finland is an overstocked and unproductive hardwood or Scots pine stand, where good tending practices have been neglected. The trees in these stands are not large enough to qualify for being used for pulpwood (Hakkila 2004). The handling of small trees limits the capacity of the logging machine and tends to decrease the productivity of work and thus increase the logging costs. To

reach the goal of the Finnish energy and climate strategies, it is necessary that the current harvesting volume from pre-commercial thinnings (0.7 million m<sup>3</sup>), should be more than doubled to 1.6 million m<sup>3</sup> by 2010. Cost effective harvesting is, however, a precondition for the sustainable utilisation of small trees for energy purposes. Currently, pre-commercial thinning operations are subsidised for silvicultural reasons, which enables the energy wood harvesting activities for energy production. Also the emission trade enhances the competitiveness of wood fuels against fossil fuels because of the additional value of CO<sub>2</sub>-neutrality compared to fossil fuels (Ranta et al. 2007).

In Finland, logging systems in energy wood thinnings can be classified into those which are based on the manual or mechanised cutting of trees. Manual cutting is carried out using a chainsaw, which is equipped with a felling frame and this working technique is called to "lift-felling" (Harstela and Tervo 1977, Hakkila et al. 1978, Ihonen 1997). Subsequently, felled whole trees are forwarded to the landing. Two alternative systems are used in mechanised whole tree logging: 1) The traditional two-machine system (a harvester and a forwarder) and 2) the harwarder system (a single machine for all logging phases). Both the harvester and the harwarder utilise the multi-tree processing technique, which reduces handling time per tree when several trees are processed during one cycle (e.g. Johansson and Gullberg 2002). It has been estimated that currently there are 180 harvesters and 50 harwarders harvesting small diameter ( $d_{1.3} < 10$  cm) thinning wood for fuel in Finland (Kärhä 2007b) either seasonally or throughout the year. When using harvesters as a base machine, the cutting of whole trees can be done with purpose built accumulating felling heads or by normal harvester heads equipped with multi-tree handling accessories.

Comminution is the primary element of the forest chip supply chain affecting the whole system (Asikainen 1995), because the location of the comminution determines the form of the material to be transported. When the comminution is done at the end use facility or at the terminal, the comminution is conducted in a centralised area and off-road transportation is followed by long distance transportation. In the system where comminution takes place at the roadside landing,

it and long-distance transportation are linked to each other. In the terrain comminution system, forwarding and comminution work phases are conducted by a single machine in one pass (Ranta 2002).

Centralised comminution at the end use facility or at the terminal enables the efficient use of comminution machines which are either stationary or mobile. Raw material is transported in an unprocessed form, the result of which is a low bulk density and therefore higher transportation costs compared to comminuted or compacted material (Angus-Hankin et al. 1995). In Finland the size of the load is usually limited by the frame volume rather than the legal mass capacity (Ranta and Rinne 2006). Comminution and long distance transportation are independent of each other, which results in a high degree of capacity utilisation and thus relatively low comminution costs. However, extensive investment in the centralised comminution system presupposes full employment and large annual comminution volumes (Asikainen et al. 2001).

Comminution will approximately double the bulk density of the transported material (Angus-Hankin et al. 1995) and thus significantly reduce the transportation costs. When the comminution is done at the landing, the chipper and truck are dependent on each other and some part of the working time of the chippers or chip trucks may be wasted in stoppages or waiting (Asikainen 1995). The idling time reduces the operational efficiency of the supply chain and increases costs. A terrain chipper is more expensive and heavy compared to a forwarder as well the load volume is quite small and hence the forwarding distance must be short and the ground has to be flat and firm (Ranta 2002). The terrain chipper is also more likely to have technical failures which also increases the harvesting costs (Ranta 2002). Furthermore, in the wintertime the high snow or water content might spoil the heating value of fuel chips.

In Finland the procurement of small-sized thinning wood chips is mainly based on chipping at the roadside storage (73%) or at the terminal (24%) (Kärhä 2007a). Comminution at the end use facility is not so common in thinning wood harvesting compared to the logging residue or stump wood chip production. Comminution at the

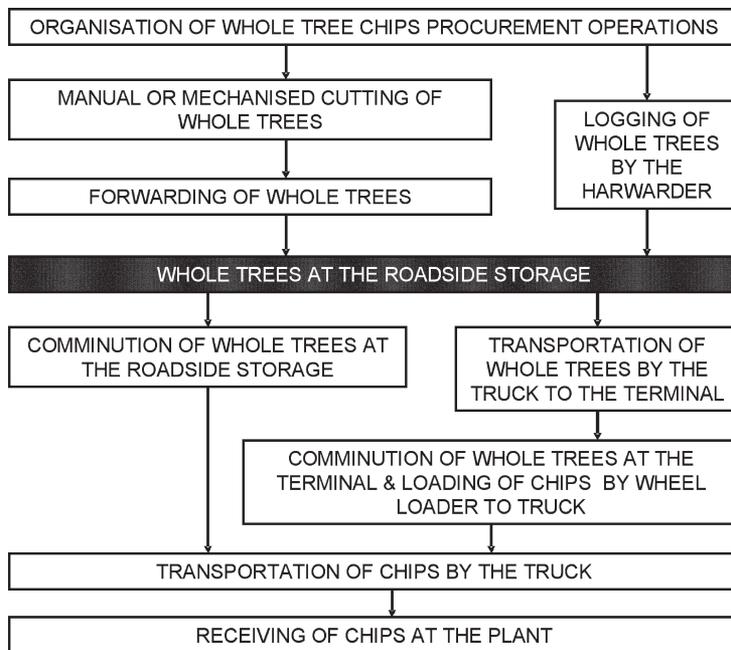
landing is a suitable and rather cost competitive procurement system for all size category power and heating plants. Terminals operate as a buffer storage, which enables a more secure supply of fuel chips and is also a process management tool for the whole supply chain. The terminal is also a compromise between comminution at the landing and at the plant (Vartiamaäki et al. 2006). The raw material is transported in an unprocessed form to the terminal and delivered to the plant as chips. Comminution in the terrain is a seldom used harvesting method in Finland (Kärhä 2007b), especially in the pre-commercial thinning wood operations.

The aim of this study was to compare and analyse the most common logging systems and supply chains of forest chips that are used in pre-commercial thinnings in Finland by using existing and published productivity models and parameters. The study was based on a cost and productivity comparison of the harvesting systems at a stand level. The compared logging systems were: the manual and the mechanised cutting of whole trees and forwarding by the forwarder and logging of whole trees by the harwarder. In the supply chain comparison the comminution was done by truck mounted chipper either at the roadside storage or at the terminal. The results were expressed as Euros per solid cubic metre (€/m<sup>3</sup>)

## 2 Material and Methods

In this study the comparison of the alternative supply chains and the logging systems started with organising the procurement activities, continuing onto the logging, comminution and transportation and finally to delivering the chips to the end user. The supply chains and the main work stages are illustrated in Fig. 1. In this study the volumes were expressed as solid cubic metres (m<sup>3</sup>) or litres (l).

The costs of the organisation are connected to the acquisition and selection of stands, planning and supervision of the work, scheduling the wood fuel procurement and delivery, and also to the payments and invoicing (Ranta 2002). The forest chips procurement operations are quite often integrated into other activities such as roundwood or



**Fig. 1.** The logging systems and supply chains of this study by the main work stages.

industrial wood waste procurement or into peat production (Asikainen 2001). In this study the overhead costs were estimated to be 3.61 €/m<sup>3</sup>, which corresponds to the average organisation cost of industrial roundwood procurement in Finland (Kariniemi 2006). The organisation cost was set as constant for all logging systems and supply chains in this study.

The cost of the manual cutting of whole trees was based on a collective labour agreement (Met-säalan palkkaus 2006) and productivity models for the felling bunching of whole trees (Vastamäki and Örn 1995). The working method used was the so-called “lift-felling”. The total daily cost of the manual worker equipped with the chainsaw and the felling frame was 156 € in this study. In the mechanised cutting, the productivity was based on a time consumption model for the thinning harvester equipped with an accumulating felling head (Laitila et al. 2004). In the productivity model, the maximum number of trees per crane cycle was limited to four trees, otherwise with the small tree volumes the productivity values would have been invalid. The harvester’s effective time ( $E_0$ ) productivity was converted to the gross effective

time productivity ( $E_{15}$ ), which included delays shorter than 15 min, by the coefficient 1.3.

The productivity of forwarding whole trees after manual and mechanised cutting was calculated on the basis of Laitila et al. (2007) time consumption models and the forwarder’s effective time ( $E_0$ ) productivity were converted to the gross effective time productivity ( $E_{15}$ ) by the coefficient 1.2. In the harwarder system, the productivity was calculated for the harwarder based on a conventional medium-duty forwarder (Laitila and Asikainen 2006). The effective time productivity ( $E_0$ ) of the harwarder was converted to the gross effective time ( $E_{15}$ ) productivity by the coefficient 1.25. The operating hour productivity coefficients for logging machines were based on estimates of the author, as follow-up study data from pre-commercial thinnings was not available and the data from the roundwood harvesting was considered invalid for this study.

The forwarder-based harwarder used a working method in which the machine firstly reversed into the stand and opened the strip road. The removed trees were piled alongside the striproad and the driver estimated the length of the striproad so

that there was enough wood for one load. After opening the strip road, on the way out of the stand, the harwarder thinned both sides of the opened strip road and loaded the processed trees onto the bunk (Laitila and Asikainen 2006). The lifting height of the harwarder crane was not sufficient to enable the lifting of the accumulated tree bunches straight onto the bunk. Hence, the accumulated bunches had to be laid on the ground before taking a new grip for loading (Laitila and Asikainen 2006). The new grip for the loading was in the middle of the tree bunch.

In the long distance transportation the driving speed and the transportation time were calculated as a function of the transporting distance according to the time consumption model for chip trucks (Ranta 2002). In this study the trucks were assumed to drive to the destination fully loaded and return empty to the starting point.

The logging cost calculations were made for a stand where the forwarding distance was 200 metres, the removal of energy wood was 60 m<sup>3</sup> per hectare and the stand area was 2.0 hectares. The average size of the removed whole trees was 30 litres. The tree species composition at the stand was: birch 60% (*Betula pendula* or *pubescens*), pine 25% (*Pinus sylvestris*) and other broadleaf trees 15% (e.g. *Populus tremula* or *Alnus incana*). A stumpage price for the harvested raw material was not considered while transferring cost of machines were included in the operating hourly costs of the machines

The load size was 6.0 m<sup>3</sup> both for the forwarder and the harwarder when forwarding whole trees (Laitila and Asikainen 2006, Laitila et al. 2007). The transport distance from the stand to the terminal or to the end use facility was 40 km. Furthermore, in the supply chain, which was based on chipping at terminal, the transportation distance for the chips from the terminal to the end use facility was 10 km. The load volume of the truck-trailer unit was estimated to be 25 m<sup>3</sup> when transporting whole trees and 44 m<sup>3</sup>, when transporting chips either from the roadside storage or from the terminal to the end use facility (Fig. 1). The chipper's operating hourly productivity was estimated to be 34 m<sup>3</sup>/E<sub>15</sub> at the roadside storage (85 loose-m<sup>3</sup>) and 44 m<sup>3</sup>/E<sub>15</sub> at the terminal (110 loose-m<sup>3</sup>).

The loading time of the truck-trailer unit was

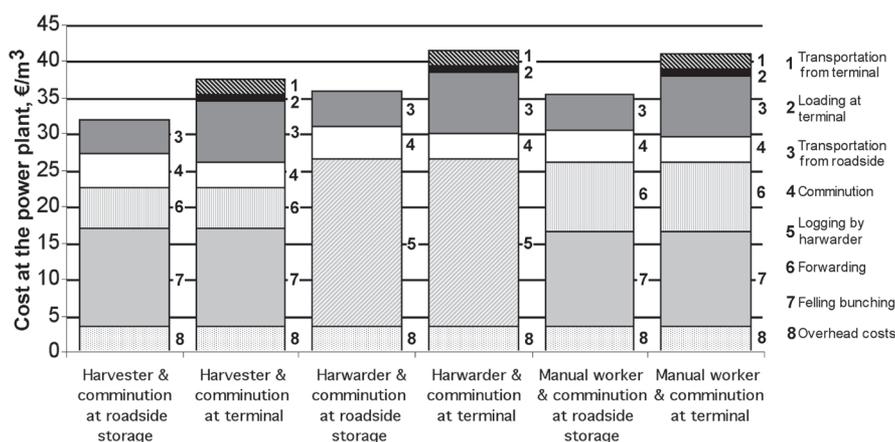
estimated to be 1.0 hour when transporting whole trees from the roadside storage to the terminal. The unloading time of whole trees was estimated to be 0.8 hours, which also included the auxiliary and waiting time at the terminal. The loading time of the truck-trailer unit was 1.29 hours (equal to chipping time), when transporting chips from the roadside storage to the end-use-facility. At the terminal the loading time of chips was 0.37 hours and the work was done using a wheel loader. The cost of the loading work at the terminal was 0.9 €/m<sup>3</sup> (Ala-Fossi, Antti, Lappeenranta University of Technology, Finland – personal communication 2007). The unloading time of chips at the end-use-facility was estimated to be 0.8 hours, which also included the auxiliary and waiting time.

The hourly costs (excluding VAT) of the machines and transport vehicles were calculated per gross effective hour (E<sub>15</sub>) by the machine cost calculation method (e.g. Harstela 1993). For the transport vehicles the hourly cost was divided between driving and terminal times. The annual working time was standardised as 2600 operating hours for all machines and transport vehicles. The total operating machine costs included both time-dependent costs (capital depreciation, interest expenses, labour costs, insurance fees, and administration expenses) and variable operating expenses (fuel, repair, service and machine transfers). The calculation values for labour costs, fuel, insurance fees, repairs and service expenses were obtained from Koneyrittäjien Liitto ry (The Trade Association of Finnish Forestry and Earth Moving Contractors) and Metsäalan Kuljetusyrittäjät ry (Association of Forest Industry Road Carriers). Machine and transport vehicle average prices were acquired from the manufacturers.

The utilisation degrees of logging machines were obtained from the study of industrial roundwood harvesting (Kärhä et al. 2007b) and the chipper's utilisation degrees at the terminal or roadside use were derived from the study of Ikäheimo and Asikainen (1998). The utilisation degree of the transport vehicles was obtained from the average time consumption of timber trucking in Finland (Alve 1988, Nurminen and Heinonen 2007) while the utilisation degree parameter was set as the same for both truck-trailer types. The risk and profit margins for the entrepreneur were 5% in the cost calculations.

**Table 1.** Data used in the hourly cost calculation.

Machine or transporting vehicle	Purchase price, € (VAT 0%)	Degree of machine utilisation, %	Operating hour cost, €/E <sub>15</sub>
Harvester	285 000	80	71
Forwarder	225 000	85	60
Harwarder	270 000	83	67
Truck-trailer unit for whole trees transportation	278 000	90	
– Driving time			77
– Terminal time			51
Truck-trailer unit for chip transportation	232 000	90	
– Driving time			72
– Terminal time			47
Truck mounted chipper	400 000		
– At the roadside landing		65	154
– At the terminal		85	139



**Fig. 2.** Cost of whole tree chips by main work stages at the power plant, €/m<sup>3</sup>.

Capital costs were calculated by the annuity method, by using an interest rate of 6% and salvage value of 40% for logging machines and transport vehicles. The lifespan of the logging machines and transport vehicles were standardised as 12000 operating hours (E<sub>15</sub>). Table 1 shows the purchase prices (excluding VAT) used in the cost estimates in this study as well the utilisation degree values of logging machines and transportation vehicles. Hourly costs are presented in Euros per operating hour (€/E<sub>15</sub>).

### 3 Results

#### 3.1 Procurement Cost of Whole Tree Chips

The procurement cost of the whole tree chips varied between 31.9 and 41.6 €/m<sup>3</sup> at the end use facility depending on the logging system and supply chain used (Fig. 2). The logging system based on the harvester with the accumulating felling head was the cheapest while the harwarder system was the most expensive. The logging cost at the roadside storage was 19.1 €/m<sup>3</sup> for the two-machine system, 22.6 €/m<sup>3</sup> for the system based on manual cutting and 23.0 €/m<sup>3</sup> for the

harwarder system. The supply chain based on the comminution at the roadside landing was found to be significantly cheaper compared to the comminution at the terminal. The cost difference between supply chains was 5.7 €/m<sup>3</sup>. The overall cost of chipping, handling and transporting were altogether 9.2–15.0 €/m<sup>3</sup> depending on the supply chain used for the production of whole tree chips.

The felling bunching was the most expensive work stage in the procurement of whole tree chips (12.9–13.5 €/m<sup>3</sup>) (Fig. 2). The cost difference in the felling bunching between manual and mechanised cutting was small, nevertheless the manual felling bunching was a 0.6 €/m<sup>3</sup> cheaper compared to the mechanised felling bunching of whole trees when the tree volume was 30 litres (Fig. 2). Whereas in the forwarding, the cost of manual felled trees (9.6 €/m<sup>3</sup>) was almost double that of mechanised felled trees (5.6 €/m<sup>3</sup>). Also in the fully-mechanised logging of whole trees, the cost difference between two-machine and harwarder based logging systems was significant, 3.9 €/m<sup>3</sup> (Fig. 2).

### 3.2 The Analysis of Logging Productivity

Figures 3 and 4 explain the noted differences based on productivity equations for the forwarding and mechanised cutting of whole trees (Laitila et al. 2004, Laitila and Asikainen 2006, Laitila et al. 2007). Table 2 details the size of the loading stop (volume of loading point) and grapple load (m<sup>3</sup>), when forwarding mechanically or manually felled whole trees by forwarder or harwarder system, as well the time consumption for the loading work (s/m<sup>3</sup>). In the productivity comparison of whole tree logging, the time consumption of driving with or without load were similar for the forwarder and the harwarder, since the driving speed of the forwarder based harwarder does not differ from a standard forwarder's driving speed (Laitila and Asikainen 2006). Also the unloading time of the forwarder at the roadside landing was independent of the felling bunching method. In addition Table 3 presents the productivity parameters of the mechanised cutting by both harvester and harwarder, when the removal of whole trees were 60 m<sup>3</sup>/ha and 2000 trees/ha and the volume

of removed trees was 30 litres.

In the harwarder system the moving times of cutting and forwarding overlap and therefore the division of moving times between forwarding and cutting was difficult to determine. In this productivity analysis, the moving time, when the harwarder thins sides of the strip road and loads the removed trees onto the load space, focused on the forwarding work. Correspondingly the time spent opening the strip road, which included both the opening and moving on the strip road, focused on the cutting and especially on the work phase of driving during cutting (Table 3).

#### 3.2.1 The Productivity Analysis of Forwarding

The productivity of the forwarding, following mechanised cutting, was 5.4 m<sup>3</sup>/E<sub>0</sub>h higher compared to the forwarding productivity of manually felled and bunched whole trees, when the forwarding distance was 200 m (Fig. 3). This significant productivity difference was explained by the fact that in the mechanised cutting the removed whole trees are bunched into large piles close to the side of the strip road which enables the driver to load full or almost full grapple loads from the well arranged piles. It clearly improves the output of loading work and thereby helps to reduce forwarding costs. After manual cutting, the piles of wood are small and scattered over a larger area. Therefore the operator had to pick up one bunch of wood, paying attention to the standing trees, then reposition the bunch on top of another pile, re-grapple both bunches, and place the grapple load either on the bunk of the forwarder or on the top of the next pile of wood (Laitila et al. 2007). This multiple-pile loading, far from the strip road, significantly decreases the loading productivity.

The harwarder's forwarding productivity was 2.9 m<sup>3</sup>/E<sub>0</sub>h lower compared to forwarder's productivity after mechanised cutting and 2.4 m<sup>3</sup>/E<sub>0</sub>h higher compared to productivity after manual cutting, when the forwarding distance was 200 m (Fig. 3). For the harwarder system (Table 2), the size of the loading stop was only 51% of the size of loading stop after mechanised felling bunching and 82% of the size after manual felling bunching

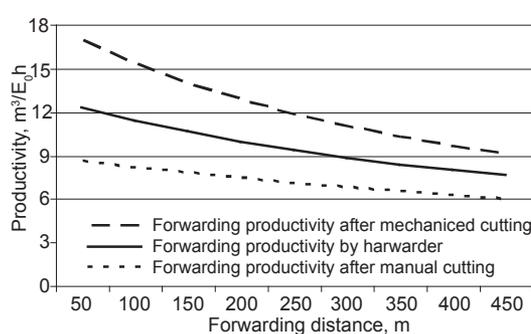
**Table 2.** Productivity parameters of forwarding work according to logging system in similar stand conditions. The removal of whole trees was 60 m<sup>3</sup>/ha at the stand.

	Forwarding after mechanised cutting	Forwarding after manual cutting	Harwarder system
Size of loading stop, m <sup>3</sup>	0.55	0.34	0.28
Size of grapple load in loading, m <sup>3</sup>	0.22	0.10	0.17
Time consumption of loading, s/m <sup>3</sup>	115	316	174
Duration of crane cycle in loading, s	25.6	31.6	29.0
Driving during loading, s/m <sup>3</sup>	28	28	46
Size of grapple load in unloading, m <sup>3</sup>	0.6	0.6	0.3
Time consumption of unloading, s/m <sup>3</sup>	43	43	50
Driving with load, s/m <sup>3</sup>	50.4	50.4	50.4
Driving unloaded, s/m <sup>3</sup>	43.2	43.2	43.2

in similar stand conditions. The size of the grapple load in the loading work was, on average, 0.17 m<sup>3</sup> for the harwarder and 0.22 m<sup>3</sup> for the forwarder after mechanised felling bunching. After manual felling bunching the average grapple load size was 0.10 m<sup>3</sup> (Table 2).

The average grapple load size means that, for example when using the harwarder system, it takes six cycles (grabbing the tree bunches and lifting them onto the bunk) before one solid cubic metre of wood has been loaded. After mechanised cutting the forwarder operator has to repeat the loading cycle 4.5 times and after manual cutting 10 times to load one solid cubic metre of wood in the corresponding stand conditions. Time consumption of the loading work by the harwarder was 174 s/m<sup>3</sup>, while for the forwarder it was 115 s/m<sup>3</sup> after mechanised cutting according to the productivity equations (Table 2). After manual cutting the time consumption for the loading work was as much as 316 s/m<sup>3</sup>. The average duration of the loading work cycle was 29 seconds for the harwarder. For the forwarder the crane cycle in the loading after mechanised cutting took, on average, 25.6 seconds and 31.6 seconds after manual cutting (Table 2).

The driving time of the forwarder between loading locations were the same, 28 s/m<sup>3</sup>, for both felling bunching methods (Table 2), as the driving distances between the loading stops were just a few metres per step (Laitila et al. 2007). The harwarder's driving time between loading stops was 46 s/m<sup>3</sup>, which was almost double that of the forwarder. This is explained by the fact that the movements of harwarder during cutting

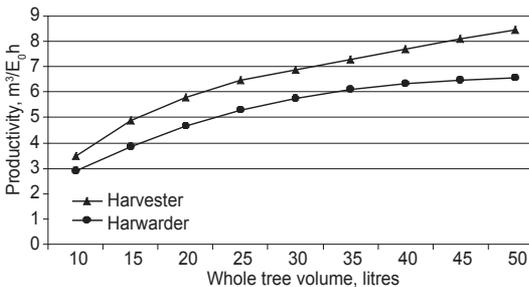
**Fig. 3.** Productivity ( $E_0h$ ) of forwarding as a function of forwarding distance after mechanised and manual cutting bunching and by harwarder system. The removal of whole trees was 60 m<sup>3</sup>/ha.

and loading were principally dependent on the thinning work.

With the forwarder, the average grapple load size in unloading was 0.6 m<sup>3</sup> whilst the harwarder's was just half of that (Table 2). The explanation for this significant difference is the structure of the harwarder's grapple. It is designed both for cutting and loading and thus the compromise grapple is not as efficient as the purpose-built timber grapple. In the unloading work the differences were not so large. For the forwarder the unloading took 43 s/m<sup>3</sup> while for the harwarder the unloading productivity at the roadside landing was just 16% slower (Table 2). Obviously the movement speed of the harwarder crane had been adjusted faster compared to the movement speed of forwarder crane in unloading.

**Table 3.** Productivity parameters of mechanised cutting work in thinnings depending on logging system, when the removal of whole trees was 60 m<sup>3</sup>/ha and tree volume was 30 litres.

	Energy wood harvester	harwarder
Time consumption of cutting, s/m <sup>3</sup>	476	441
Driving during cutting, s/m <sup>3</sup>	49	184
Total, s/m <sup>3</sup>	525	625



**Fig. 4.** Productivity ( $E_{0h}$ ) of mechanised cutting as a function of tree volume by energy wood harvester and harwarder. Removal of whole trees was 60 m<sup>3</sup>/ha and number of removed trees 6000–1200 trees/ha.

### 3.2.2 Productivity Analysis of Mechanized Cutting

In the mechanised cutting of thinning wood, the harvester's productivity was 1.1 m<sup>3</sup>/E<sub>0h</sub> higher compared to the harwarder's productivity in thinning (Fig. 4), when the tree volume was 30 litres and removal was 60 m<sup>3</sup> and 2000 trees per hectare. Time consumption of cutting of whole trees by the harvester was 476 s/m<sup>3</sup> and 441s/m<sup>3</sup> for the harwarder (Table 3), which actually corresponds to the cutting time when thinning the sides of the strip road. The driving time consumption during cutting was 49 s/m<sup>3</sup> for the harvester while for the harwarder the moving time was more than three times longer (Table 3). In the harwarder system the moving time on the strip road was as much as 184 s/m<sup>3</sup>. For the forwarder based harwarder, the strip road opening is quite slow, as it has to operate the crane over the bunk (Laitila and Asikainen 2006). This means that the crane's

reach in the driving direction is very short and the extent to which the machine can be used to open up the strip road for itself is small. In the study of Laitila and Asikainen (2006) strip road opening was almost 18% of the total effective logging time.

### 3.3 Sensitivity Analysis of Cost Parameters and Harvesting Conditions

Figure 5 summarises the logging time consumption per operating hour and solid volume, when harvesting whole trees by the two-machine system or by the harwarder. The logging time consumption of the two-machine system was 0.28 operating hour per whole tree m<sup>3</sup>, of which the forwarding accounted for 0.09 E<sub>15h</sub>/m<sup>3</sup> and felling bunching by the harvester 0.19 E<sub>15h</sub>/m<sup>3</sup> (Fig. 5). The logging time consumption of the harwarder was 0.34 E<sub>15h</sub>/m<sup>3</sup>. The difference in the logging time consumption per m<sup>3</sup>, 0.06 E<sub>15h</sub>/m<sup>3</sup>, is explained by the productivity elements, which are detailed in Figs. 3 and 4 and Tables 2 and 3. Also the operating hour productivity coefficients (1.25, 1.20 or 1.30) which were used in the assessment for logging machines naturally made a significant difference. The combined productivity of the two-machine system per operating hour (E<sub>15h</sub>) was 3.5 m<sup>3</sup> and the corresponding productivity of the harwarder was 2.9 m<sup>3</sup>.

If a sensitivity analysis is conducted, in which it is assumed that the full-mechanised logging systems' operating hour productivity will remain constant (Fig. 5), the hourly cost of the harwarder should decrease to 55.5 €/h, in order to reach the same logging cost as when using the two-machine system. Correspondingly the hourly cost of the forwarder should increase to 102 €/h or harvester's to 92 €/h in order to reach the logging cost of the harwarder system (Fig. 2). In proportion, if it is supposed that the hourly cost of the logging machines remain constant, the operating time consumption per m<sup>3</sup> of the harwarder logging should decrease to 0.285 E<sub>15h</sub>/m<sup>3</sup> in order to reach the same costs of using the two-machine system. The time consumption of 0.285 E<sub>15h</sub>/m<sup>3</sup> is equal to the productivity of 3.5 m<sup>3</sup>/E<sub>15h</sub>, which means that productivity should increase by 0.6 m<sup>3</sup>/E<sub>15h</sub> or 20% from the current productivity level.

Figure 6 presents a sensitivity analysis of logging costs as a function of whole tree volume, when the logging is based on manual or mechanized cutting or work is done by the harwarder. In the cost comparison the tree volume varied between 10–50 litres, whereas the forwarding distance (200 m) and the removal (60 m<sup>3</sup>/ha) were constant. The break-even point for the logging cost of the manual worker-forwarder system and the harvester-forwarder system was when the tree volume was about 14 litres (Fig. 6). For the larger tree volumes the logging costs of the harvester-forwarder system were significantly lower than the logging costs of the manual worker-forwarder system. The logging costs of the manual worker-forwarder system were, for all tree volumes lower, than the logging costs for the harwarder (Fig. 6). However, when the tree volume was larger than 23 litres, the logging costs of the manual worker-system and the harwarder system were almost equal.

The removal per hectare is a significant cost factor in the logging of whole trees, since it affects the number of removed trees in thinnings as well the concentration of whole trees alongside the strip road in the forwarding. Also the forwarding distance affects the logging costs of the whole trees. Fig. 7 shows the logging costs of the harvester-forwarder and the manual worker-forwarder systems as well the harwarder system in differing stand conditions. In the assessment, the whole tree removals were either 45, 60 or 75 m<sup>3</sup>/ha while the forwarding distance varied between 25–450 metres. The volume of the removed trees was set as constant (30 litres), but the number of removed trees varied as a function of the removal per hectare (1500, 2000 or 2500 trees per hectare).

The harvester-forwarder system was the most cost effective logging system for all the stand conditions (Fig. 7). For the 200 metres forwarding distance, the logging costs were 20.8, 19.1 or 17.6 €/m<sup>3</sup>, when whole tree removals were 45, 60 or 75 m<sup>3</sup>/ha, respectively. A lengthening in the forwarding distance from 25 metres to 450 metres increased the logging cost by about 20–24% when using the two-machine system.

An increase in the whole tree removal per hectare improved the cost competitiveness of the harwarder system compared to the manual worker-

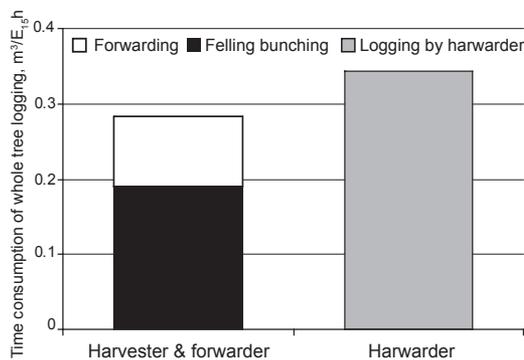


Fig. 5. Logging time (E<sub>15h</sub>) consumption per solid whole tree cubic meter (m<sup>3</sup>) by the two-machine system and by harwarder, when the removal was 60 m<sup>3</sup>/ha, tree volume 30 litres and forwarding distance 200 metres.

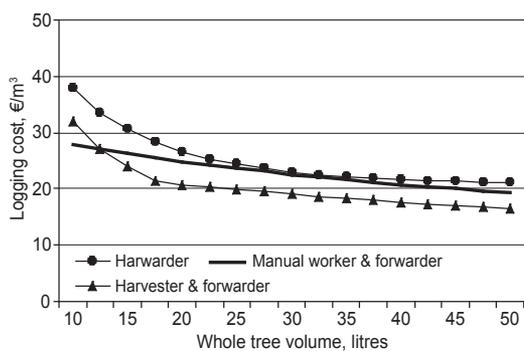
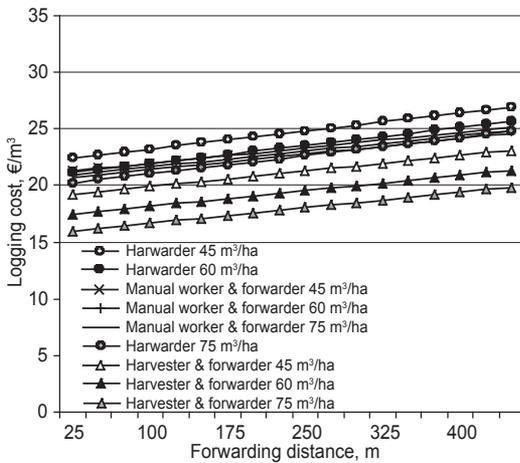


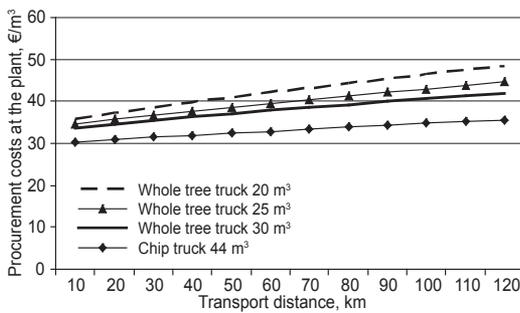
Fig. 6. Logging cost (€/m<sup>3</sup>), when the removal was 60 m<sup>3</sup>/ha, the tree volume 10–50 litres and the forwarding distance 200 metres.

forwarder system whereas the lengthening in the forwarding distance made it worse (Fig. 7). When the removal per hectare was 75 m<sup>3</sup>/ha, the logging costs for the harwarder were cheaper compared to the manual worker-forwarder system, up to a forwarding distance of 325 metres. In stands where the removal of whole trees was either 45 or 60 m<sup>3</sup>/ha the manual worker-forwarder system was the more cost effective in all forwarding distances compared to the harwarder system.

For the harwarder system an increase in the removal from 60 m<sup>3</sup>/ha to 75 m<sup>3</sup>/ha reduced the logging cost by about 0.9 €/m<sup>3</sup>, when the forwarding distance was 200 metres. Correspondingly, a decrease in the removal from 60 m<sup>3</sup>/ha to 45



**Fig. 7.** Logging cost (€/m<sup>3</sup>), when the removal at the stand were 45–75 m<sup>3</sup>/ha, tree volume 30 litres and forwarding distance 25–450 metres.



**Fig. 8.** Procurement cost comparison of supply chains as a function of transport distance and load volume of trucking.

m<sup>3</sup>/ha, increased the logging costs by about 1.3 €/m<sup>3</sup>. A lengthening in the forwarding distance from 25 metres to 450 metres increased the logging costs of the harwarder by about 20–22%, which in Euros corresponds to a value of 4.5 €/m<sup>3</sup>. In the manual worker-forwarder system the changes in the removal affected the logging cost by just 1–1.3%. A lengthening in the forwarding distance from 25 metres to 450 metres increased the logging costs of the manual worker-forwarder system by about 18–19%.

Figure 8 shows the procurement costs of the whole tree chips as a function of the road transporting distance, when the comminution took place at the roadside landing or at the terminal.

The logging was done using the two-machine system and the stand conditions and other parameters were the same as presented in Fig. 2. The transporting cost of the supply chain based on chipping at the terminal were calculated for three whole tree truck load volume alternatives, which were either 20, 25 or 30 m<sup>3</sup> (Fig. 8). The cost interactions (“hot chain”) of chipping at landing and transporting, depending on the transporting distance and number of trucks, were not considered in this study.

The supply chain based on chipping at the roadside landing was the most cost effective system in all transporting distances (Fig. 8). The cost saving compared to the chipping at terminal system was 4.3 €/m<sup>3</sup>, when the transporting distance was 10 km and the load volume of the truck-trailer unit was 25 m<sup>3</sup>. An increase in the transport distance from 10 km to 120 km increased the cost difference to 9.0 €/m<sup>3</sup>. An increase in the load volume of the truck-trailer unit from 25 to 30 m<sup>3</sup> reduced the corresponding cost difference to 3.4–6.5 €/m<sup>3</sup>. When the load volume of the truck-trailer unit was 20 m<sup>3</sup>, the cost was 6.5–12.9 €/m<sup>3</sup> higher compared to system in which the chipping was done at the roadside landing. The lengthening in the transport distance from 10 km to 120 km increased the procurements costs by 18% when transporting chips. When transporting whole trees, the corresponding cost increases were 25–35%, depending on the load volume of the truck-trailer unit (Fig. 8).

## 4 Discussion and Conclusions

This study determined and compared the procurement cost of whole tree chips when using supply chains based on comminution at the roadside landing or at the terminal and identified the bottlenecks in the logging systems. The results, concerning the factors affecting the productivity of the logging systems, were logical whilst results concerning the procurement costs of chips were reasonable. The costs of fuel chips were 31.9–41.6 €/m<sup>3</sup> at the plant or 14.9–19.4 €/MWh, when the moisture content of chips was 40%. In 2006 the average price of forest chips was 11.95 €/MWh (Ylitalo 2007). This means that the state

subsidies or other subventions for small-diameter tree harvesting are still needed to maintain the procurement activities and reach the goals of Finland's energy strategies regarding thinnings.

The two-machine system was found to be the most cost competitive logging system in pre-commercial thinning thanks to both the efficient cutting and, especially, forwarding work. In the manual worker based logging the costs of felling bunching were equal to the mechanised system, whereas for forwarding the costs were almost double. The logging costs were found to be highest when using the harwarder system, but for larger tree volumes and removals the costs were almost equal to the manual worker based logging. The supply chain based on chipping at roadside landing was more cost efficient compared to the terminal chipping system. The lower comminution costs at the terminal were not enough to cover the higher road transportation costs for the unprocessed material to the terminal, handling costs of chips at the terminal or the delivery costs to the end use facility.

This comparison study was made at the stand level, which meant that the normal fluctuation of interactions, for example, in cutting, forwarding, chipping, transporting and receiving of fuel chips at the plant were not considered. The fluctuation of interactions directly affects the degrees of utilisation of machines and vehicles and also the number of machines and vehicles which are needed. In this study as a result of not considering the normal fluctuation of interactions meant that the hourly cost of machines and vehicles were constant when making sensitivity analysis according to the removal at stand as well as the forwarding or transporting distance. In order to get more realistic information of the real life situation discrete-event modelling of procurement systems in the prevailing operating environment is required (Asikainen 1995). The utilisation of detailed stand data of raw material resources with spatial information improves the accuracy of the results (Asikainen et al. 2001, Ranta 2002, Väättäin et al. 2007).

The impact of interactions that lead to waiting and queuing resulting in increased costs has been noted in several forest technology studies (e.g. Kuitto and Rieppo 1993, Asikainen 1995, Väättäin et al. 2000, Väättäin et al. 2005). For

example in the cost of chipping and transporting the bias varies between 12–20% (Asikainen 1995) depending on the transportation distance if the interactions of chipping and transporting capacity are not considered. In this study the bias means that the cost difference between supply chains based on comminution either at the roadside landing or at the terminal is obviously not as large at the operational level or in the real life situation.

Apparently the same bias exists in the logging cost comparison of the harwarder and two-machine systems because in the two-machine system there is a significant difference in the cutting (Fig. 4) and forwarding productivity, therefore the forwarding capacity can not be fully utilised. In practice this productivity imbalance is balanced, for example, by the work shift or compensatory extra work arrangements. The common argument when promoting the harwarder system is that the unit costs per logged volume are a little bit lower in comparison to the two-machine system, even though the combined productivity of harvester and forwarder is higher. One logging machine is easier to operate in a cost effective way compared to the two-machine system in a real life situation. The annual cost savings are mainly gained in lower capital and relocation costs. Cost savings in relocation originate when translocating one machine instead of two (Asikainen 2004). Also the distances in translocation are in some cases shorter because of the smaller operating area. The operating area is proportional to the annual output of a harwarder which is, in similar conditions, smaller than the annual output of the two-machine system.

The annual productivity of a harvester equipped with an accumulating felling head is about 14 000 m<sup>3</sup> for the stand conditions and operating environment reported in this study. The corresponding logging productivity of the harwarder is 7600 m<sup>3</sup>. The annual productivity of a forwarder is 28 000 m<sup>3</sup> after mechanised cutting and 16 000 m<sup>3</sup> after manual cutting. The yearly output of a manual worker is 2700 m<sup>3</sup>. According to the goals of the Finnish energy and climate strategies one-third of the 5 million m<sup>3</sup> total forest chips volume should be harvested from thinnings (Hakkila 2005). To reach this goal, 122 full year employed harvesters and 60 forwarders or 220 harwarders will be required. If the work is done manually, 600

manual workers would have to be employed full time with 100 forwarders also being required. However, it should be noted that in the near future there will be an increased shortage of professional manual workers as well rising labour costs which will make this alternative impractical. As a result of efficient forwarding, mechanised logging is currently cheaper than the manual worker based logging. Furthermore, recently logging in pre-commercial thinning has become increasingly mechanised in Finland. Nowadays Finnish forest companies do not use manual workers when logging whole trees from pre-commercial thinnings.

On the basis of the sensitivity analysis made in this study (Fig. 5), the cost savings at the operational level, when using a harwarder system, should be significant compared to the conventional two-machine system. The hourly costs which were attained for the forwarder and the harvester in the sensitivity analysis, when the logging costs were set as the same as the harwarder, were at such a high level that it is not practical if using normal machine operating hours per year or utilisation degrees of logging machines in a Finnish operating environment. Hence, it seems that the operational benefits are not sufficient to reach the cost competitiveness of the harwarder system. It also calls for improvements to the logging machine and devices as well to the working techniques of the harwarder.

The two-pass system, which is the working technique used in this study, requires that the harwarder drives twice on the strip road in the stand: first reversing into the forest while opening the strip road and then driving back while thinning and loading the processed trees. According to Björheden (1999), in roundwood harvesting, the total travel time of a two-machine system was 4.5–5.0 times and with a harwarder 2.5–3.0 times the total length of the strip roads. In the Finnish thinning comparison, the distance travelled with a harwarder was 309 metres/m<sup>3</sup> and 15 450 metres/ha, with a two-machine system it was 326 metres/m<sup>3</sup> and 16 300 metres/ha, when harvesting industrial roundwood (Sirén and Tantt 2001). The differences in first thinning conditions showed that the capacity to combine work elements in the case of the harwarder was under utilised in practical work, even though the structure of the

base machine should have facilitated this (Sirén and Aaltio 2003).

According to a study by Metsäteho (Kärhä et al. 2006, Kärhä 2006), when applying a working method in which the strip road opening, thinning and loading were integrated into one pass, the productivity was about 5% higher compared to the productivity of the two-pass method. Applying the one-pass method instead of the two-pass method halves the moving time on the strip road, though it also sets greater demands on the operator, when planning the work and strip road network within the stand. With a full load it is a challenging task to find a route back to the roadside landing, because reversing in thinning conditions is extremely difficult (Kärhä et al. 2006). Therefore in practice the logging by harwarder is usually a combination of one- and two-pass methods. The one-pass method can be adopted by all forwarder based harwarders in which it is possible to operate the crane over the machine cabin and in so doing open up a strip road for the machine.

Simultaneous cutting, accumulation and loading of the trees during the same crane cycle improves the productivity of the harwarder as the crane movements of two separate work phases are integrated into one crane movement. In this study the effective working time was wasted for separate stacking and loading due to the incompatibility of the crane for the harwarder system (Laitila and Asikainen 2006). The lifting height of the crane was insufficient to enable the lifting of the accumulated tree bunches straight onto the bunk. The new grip for the loading was located in the middle of the tree bunch. In the study of Metsäteho (Kärhä et al. 2006, Kärhä 2006) the stages of cutting and forest haulage overlapped effectively as a result of the development of the logging machine and devices. The cutting time of the harwarders was 8% less than that of the harvesters equipped with an accumulating felling head. Furthermore, the loading productivity was 13–17% faster than that of the forwarders even though the size of the loading stop was significantly smaller. The size of the loading stop of the harwarder supports the findings of this study (Table 2). Likewise the unloading was slower and the size of unloading bunch was smaller than with the forwarder (Kärhä et al. 2006, Kärhä 2006).

In this study significant differences were noted

in the moving times between working locations when operating with a harwarder, forwarder or with a harvester in similar stand circumstances. The findings related to the moving times is inconsistent with the findings of the study of Metsäteho (Kärhä et al. 2006, Kärhä 2006), which did not find significant differences between the moving times of the harwarders and two-machine system. Partly this difference might be explained by the stand circumstances in the time studies and the operator's skills. However it should be logical that, for example, the operator's limited visibility from the cabin of the forwarder based harwarder compared to the visibility from the harvester's cabin and the short crane reach when operating over the bunk, to some extent, reduce the comparable productivity of the harwarder, especially when opening the strip road. In the study of Metsäteho (Kärhä et al. 2006, Kärhä 2006) 25 out of 35 loads were logged utilising the same working technique and machine type which were used in the time study of Laitila and Asikainen (2006). The harwarder operators working experience were 0.5–2 years in the study of Kärhä et al. (2006). In the study of Laitila and Asikainen (2006) the operator-contractor had five months practice in harwarder work and several years working experience related to logging and earth moving work.

According to the study of Metsäteho (Kärhä et al. 2006, Kärhä 2006) the harvesting costs of the harwarder and two-machine system were similar. Nevertheless, the results indicated that the harwarders are the most competitive in harvesting sites where the forwarding distances are short (<150 m), the whole trees to be harvested are relatively small (< 20 litres), and the total volume of whole trees removed is relatively low (< 55 m<sup>3</sup>/ha or < 100 m<sup>3</sup>/stand). These findings are in line with the findings of earlier studies of harwarders in industrial roundwood harvesting (Sirén and Aaltio 2003, Wester and Eliasson 2003, Asikainen 2004, Kärhä et al. 2007b).

Kärhä et al. (2006) conducted a follow-up study which totalled 14 000 m<sup>3</sup> of whole trees logged using a harwarder. According to the follow-up study, the average removal of whole trees was 52 m<sup>3</sup>/ha (variation 25–132 m<sup>3</sup>/ha), the area of the stand was 3.7 ha, forwarding distance was 309 m (variation 94–871 m) and the removal

of whole trees per stand was 185 m<sup>3</sup> (variation 31–932 m<sup>3</sup>). When comparing the recommendations of the cost efficient use of harwarders and the real life operating environment, it seems that contractors do not have a clear concept of how to utilise harwarders or the machine concept is not suitable for the stand structure. Obviously the current low annual harvesting volumes of whole trees limit the stand selection and cost effective utilisation of harwarders as part of the harvesting fleet. A lack of foreknowledge of the stand locations and conditions limits the targeting of logging systems to the stands which are the most optimal for harwarders (Jylhä et al. 2006, Väätäinen et al. 2007). According to the study of Väätäinen et al. (2007) the harwarder was the most cost competitive system in 11.7–22.44% of all stands or 1.9–7.5% of the total harvested roundwood volume. The discrete-event study of the cost competitiveness of harwarders in cut-to-length logging conditions was done utilising real stand data from logging operations in south-east Finland and North Ostrobothnia.

The operating hourly productivity coefficients for the logging machines used in this study were based on estimates of the author while the utilisation degrees of the forest machines were obtained from the study of industrial roundwood harvesting (Kärhä et al. 2007b). Therefore there is an urgent need for a comprehensive follow-up study for logging machines as it is obvious that the mechanical availability (MA) of logging devices for whole trees is higher compared to the MA of industrial roundwood logging equipment due to, for example, a more simplified structure of felling heads or combi-grapples with fewer components. Furthermore, research should be conducted into how the variability of the work in pre-commercial thinnings effects the operator's job satisfaction, work motivation and productivity per shift. In an 8-hour work shift the harvester operator has to collect and process 1406 trees whereas the harwarder operator needs only 777 trees per shift in order to meet the same cost level, as illustrated in Fig. 2. Correspondingly the logging costs are equal to the two-machine system, if the harwarder operator is able to harvest at least 936 trees per 8-hour work shift.

High logging costs, particularly cutting costs, are the main problems in early thinnings. In order

to increase the procurement volumes of energy wood in young stands, which is the largest unutilised source of forest fuels in Finland (Helynen et al. 2007), logging costs have to be significantly reduced. One way to do this is to improve working techniques and equipment, learning-by-doing (Junginger et al. 2005) or develop novel machine and technology solutions (Jylhä and Laitila 2007, Kärhä et al. 2007a). In the transportation phase the improvements can be targeted on maximising the delivered load up to the legal weight and dimensional limits and to the minimisation of time spent at the terminal (Angus-Hankin et al. 1995, Sikanen et al. 2005). There is also need for improvements and rationalisation in the management of procurement activities (Asikainen and Kuitto 2000) because the estimated share of overhead costs were about 10% of the total costs in this study. Another way is to improve logging conditions by considering new management alternatives for young forests (Sirén et al. 2006) and targeting logging operations to stands where the conditions are favourable for energy wood recovery. Cutting of small-sized wood (DBH 1–4 cm) should be avoided and thus improve the profitability of energy wood logging (Kärhä et al. 2005). According to Lauhanen et al. (2007) in the most unfavourable stands the thinning without recovery of energy wood might be the most reasonable solution.

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